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Test of the quark content of hadrons through the determination of electromagnetic form factors

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Abstract

The determination of the kinematical region where a reliable description of the light ions structure requires to take explicitely into account quark degrees of freedom is an open question in hadron electrodynamics. The precise determination of form factors allows a test of microscopic models on measurable quantities. We will give some examples where, due in particular to recent developments of polarization techniques, the interpretation of new, precise data can be done in a model independent way, on the basis of fundamental symmetry properties of the electromagnetic and strong interaction.

1. Introduction

The complex structure of hadrons can be described in a convenient way in terms of form factors. In a parity conserving and time invariant theory, each particle of spin S can be described in terms of $2S + 1$ elastic electromagnetic form factors, which are real functions in the space-like region and complex functions in the time-like region of momentum transfer square. The precise measurement of these form factors requires polarization experiments (except for spin zero particles, like pions or kaons). The (elastic or inelastic) electron-hadron scattering is the traditional way to determine the form factors, and it allows a direct comparison with the theory. Recent measurements at the Jefferson Laboratory essentially improved the experimental data concerning the elastic form factors of protons and deuterons up to relatively large values of momentum transfer [1-3] and a large program is under way to measure the form factors of the neutron and of the

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first nucleon resonances [4]. We will discuss the implications of these new results and show the complementarity of hadronic isoscalar probes such as polarized deuterons. Our considerations will be mainly based on fundamental symmetry properties of elementary particle interactions. We will focalize on some examples of physical problems, in the field of hadronic structure, where such symmetry analysis has been possible without using specific models.

1.1. Elastic electron-hadron scattering

In the framework of one-photon exchange, the cross section of elastic electron-hadron scattering, can be factorized in a kinematical coefficient, and a term which contains combinations of form factors called the structure functions, which depend on the four momentum transfer Q^2. As an example, the unpolarized elastic electron-hadron cross section can be generally written as:

$$\frac{d\sigma}{d\Omega} = \sigma_0 (A(Q^2) + \tan^2\frac{\theta}{2} B(Q^2)). \tag{1}$$

In principle due to the presence of the angular coefficient, $\tan^2\frac{\theta}{2}$, where θ is the electron scattering angle, a precise measurement of the cross section at two different angles, for the same Q^2, (Rosenbluth fit) can give the values of the two structure functions A and B. In the case of ep-elastic scattering, these functions are directly related to the electric and magnetic form factors, usually called G_{Ep} and G_{Mp}. However, at large Q^2 the term related to G_{Ep} becomes relatively small, and in practice the extraction of G_{Ep} from unpolarized cross section is affected by large errors. It has been shown more than thirty years ago [5] that the measurement of the polarization of the proton when the electron is longitudinally polarized, is directly related to G_{Ep}. An experimental method based on this approach could be applied only recently, due to the high intensity polarized electron beam of Jefferson Laboratory and the developement of the proton polarimeter FPP. The results, which are five times more precise than the previous ones, show clearly a deviation of the electric form factors from a dipole behavior, commonly assumed up to now in many model calculations. These data are playing a fundamental role for the test of different models, from VDM to QCD-inspired models, as constituent quark models, diquark models, bag models as well as hybrid models.

They are also important in the description of the deuteron structure, in addition to meson exchange currents, relativistic corrections.. In case of electron-deuteron scattering the situation is more complex, as the deuteron, being a spin one particle, is described by three form factors. The SF's $A(Q^2)$ and $B(Q^2)$ in Eq. (1) are quadratic combinations of the charge, quadrupole and magnetic form factors, which can be completely determined through the measurement of tensor polarization observables, in addition to the Rosenbluth separation.

Recent measurements of the structure function $A(Q^2)$ and of the polarization observable t_{20} show that the fundamental trends can be reproduced by traditional approaches based on Impulse Approximation, up to $Q^2 \leq 2$ GeV^2. However at larger values of Q^2, the new data on $A(Q^2)$ confirm a tendency previously observed [6] for a scaling of form-factors as $(Q^2)^5$. This result is consistent with a prediction of perturbative QCD [7]. It derives from simple dimensional counting, where the physical dimensional quantities are functions only of the momenta (which are large). The underlying assumption is that the scattering amplitude is the same as for free quarks in a hadron. However it has been stressed [8] that traditional appoaches can predict similar scaling laws for the cross section at large momentum transfer, but the predictions for polarization observables or individual form factors remain quite different.

A check of scaling laws in this domain has been done for other reactions, involving deuterons: π^0 photoproduction in $\gamma + d \to d + \pi^0$ [9] and deuteron photodisintegration $\gamma + d \to n + p$ [10]. The conclusions of the authors is that an 'early' scaling of the cross section is observed starting from $E_\gamma \simeq 1$ GeV. Measurements at different angles show that deviations from the expected power law appear. We would like to stress here that a comparison between the different reactions should include a discussion on the kinematical regimes: in $\gamma + d$ reactions, $Q^2 = 0$, while the total energy, s, and the momentum transfer from the γ to the detected hadron, $-t$, are large compared to the hadron mass. In case of $e + d$ reactions, the scaling behavior appears at large values of Q^2, while $t \simeq 0$ and $s \simeq M^2$, where M_d is the deuteron mass. In this respect the coherent π^0 electroproduction on deuteron, now experimentally accessible [11], should bring new pieces of information.

At the light of these experimental findings, we would like to make the following remark. Eq. (1) holds in the framework of one-photon exchange. Usually the contribution from two-photon exchange is considered to be $1/\alpha \simeq 100$ times smaller.

However, it was observed [12-15] that the simple rule of α-counting for the estimation of the relative role of two-photon contribution to the amplitude of elastic $ed-$scattering does not hold at large momentum transfer. For an 'elastic' mechanism, where the transferred momentum is equally shared between the two photons, simple estimations show that the role of two-photon exchange can become sizeable at $Q^2 \geq 1$ GeV^2, particularly in ed-elastic scattering, due to the steep decrease of the deuteron form factors. If complete calculations are very difficult, it is possible to estimate these effects from the present data, using symmetry considerations. In our approach no model for the electromagnetic form factors of hadrons or for the dynamics of the 2γ-exchange is needed: the crossing symmetry provides a relation between the elastic $e^- + h \to e^- + h$ scattering and e^+e^--annihilation: $e^+ + e^- \to \overline{h} + h$, in one-photon approximation. The crossing symmetry can be expressed by the following relation between the matrix elements $\mathcal{M}$ of the crossed processes:

$$\overline{|\mathcal{M}(eh \to eh)|^2} = f(s,t) = \overline{|\mathcal{M}(e^+e^- \to \overline{h}h)|^2}. \tag{2}$$

The line over $\mathcal{M}$ denotes the sum over the polarizations of all particles (in initial and final states). The Mandelstam variable s is the total energy and t is the momentum transfer and they delimit different kinematical regions for the annihilation and the scattering channel.

The presence of a single virtual photon in the reaction $e^+e^- \to \gamma^* \to \overline{h}h$ constrains the total angular momentum $\mathcal{J}$ and the P-parity for the $\overline{h}h-$system, to take only one possible value, $\mathcal{J}^P = 1^-$, the quantum number of the photon. In the framework of the one-photon approximation, in the general case, $\overline{|\mathcal{M}(eh \to eh)|^2}$ can be written (in CMS) as:

$$\overline{|\mathcal{M}(eh \to eh)|^2} = a(t) + b(t)\cos^2\tilde{\theta}, \tag{3}$$

where $a(t)$ and $b(t)$ are definite quadratic combinations of the electromagnetic form factors for the hadron h and $\tilde{\theta}$ is the angle of the detected hadron.

In case of the presence of 2γ in the intermediate state, in the annihilation channel, any value of the total angular momentum and space parity is allowed, because the relative 3-momentum for the 2γ-state is nonzero, contrary to the case of the one-photon mechanism. The $\overline{h}h$-system, produced through 1γ and 2γ-exchanges has different values of C-parity, because $C(\gamma) = -1$ and $C(2\gamma) = +1$. Therefore the interference of one- and two-photon contribution must be an **odd** function of $\cos\tilde{\theta}$: $\overline{\mathcal{R}e\mathcal{M}_1\mathcal{M}_2^*} = \cos\tilde{\theta}(a_0 + a_2\cos^2\tilde{\theta} + ...)$. The first attempt to obtain a quantitative upper limit of a possible 2γ-contribution, has been done in [16], on the basis of the ed elastic scattering data from three experiments [2,3,7]. The precision of the recent data data is clearly reflected in this study. Such analysis shows a deviation from the Rosenbluth linearity starting from $Q^2 \geq$ GeV/c^2 which might be due to the presence of 2γ-exchange in $ed-$elastic scattering. A detectable 2γ contribution, in a dedicated experiment, is not excluded.

The presence of 2γ-exchange in elastic hadron scattering can be experimentally searched in different ways: - through the comparison of the cross section for scattering of unpolarized electrons and positrons (by protons or deuterons) in the same kinematical conditions, - looking to the deviation from a straight line on the Rosenbluth plane - measuring specific properties of polarization phenomena: as nonzero $T - odd$ polarization observables, and violation of definite relations between T-even polarization observables and the SF $B(Q^2)$. The measurement of cross section and polarization observables bring complementary and independent pieces of information, as they test the real and imaginary part of the 2γ contribution.

The recent progress in developing polarized deuterons targets [17] and in the polarimetry of the produced deuterons [18] makes possible large accuracy measurements of vector and tensor deuteron polarization. Due to the importance of this problem for hadron electrodynamics, not only the measurements of the differential cross section are necessary, but the study of polarization phenomena, as well.

2. Inclusive $\vec{d}, p$ scattering

The selectivity of reactions such as $p(d, d')X$ or $p(\alpha, \alpha')X$ to the isoscalar part of the N^*-electroexcitation makes these processes complementary to electron-nucleon inelastic scattering, for the study of the N^*-structure. In case of polarized deuteron beam, it has been shown [19] that the ω-exchange model gives a natural and simple description of the polarization phenomena for $d + p \to d + X$. The main ingredients are the existing information about the deuteron electromagnetic form factors [20] and about the ratio r

between the longitudinal and transversal isoscalar cross sections for the excitation of the N^*-resonances [21]. No free parameters are needed to reproduce the available data on the tensor analyzing power[22].

The ω-meson is preferred, among the isoscalar mesons as σ or η, for several reasons. The $\omega NN-$ coupling is large; the ω-meson, being a spin 1 particle, can induce strong polarization effects and an energy-independent cross section. When it is considered as an *isoscalar photon*, then the cross sections and the polarization observables can be calculated from the known electromagnetic properties of the deuteron and N^*, through the vector dominance model. Moreover, due to these special properties of the $\omega-$exchange mechanism an experimental test of the validity of this model can be proposed, similarly to the Rosenbluth test of the one-photon mechanism, in case of elastic and inelastic electron-hadron scattering.

Due to the specific quark structure, the resonances, lying in the concerned mass region, such as $S_{11}(1535)$, $D_{13}(1520)$ and $S_{11}(1650)$ are characterized by a pure isovector nature of longitudinal virtual photons absorbed by the nucleons. The isoscalar longitudinal amplitudes of $S_{11}(1535)$ and $D_{13}(1520)$ electroexcitation vanish due to a specific spin-flavor symmetry, while both isoscalar and isovector longitudinal couplings of $S_{11}(1650), D_{15}(1675)$ and $D_{13}(1700)$ vanish identically. Only the Roper resonance has a nonzero isoscalar longitudinal form factor. Without excitation of the Roper resonance, $r = 0$, (in the considered kinematical region) and the value for T_{20} becomes $t-$independent: $T_{20} = -1/2\sqrt{2}$, in evident disagreement with existing data [23].

This behavior of the isoscalar form factors is essential for the correct description of the existing experimental data on the $t-$dependence of T_{20} for the process $d+p \to d+X$. Of course, this model for $d+p \to d+p$ can be improved, taking into account for example, other meson exchanges, or the effects of the strong interaction in initial and final states. However these corrections are strongly model- and parameter- dependent; the existing experimental data are not good enough to constrain the additional parameters which have to be added. In this case we loose the predictive power of our "parameter free" model. The successful description of the polarization observable T_{20} can be considered as a strong indication that the $\omega-$ exchange is the main mechanism for the considered process and that the Roper resonance is excited in this process.

3. Conclusions

In the interpretation of the experimental results it is often difficult to disentagle the particle structure from the reaction mechanism and to derive from the data, a real physical information. It is not possible to overestimate the role played by precise measurement of hadron form factors, in the test of the validity of different models and the role played by different contributions.

We have selected here a few recent examples, where on the basis of fundamental symmetry properties, it is possible to give a realistic description of the underlying properties of the hadron structure. This approach is free from many problems which arise from similar considerations in framework of parameter-dependent models .

We have illustrated through different examples:

- The recent measurements of the proton and deuteron form factors constitute a stringent test of theoretical model and will lead to a revision of light nuclei description.

- A model independent analysis of very precise measurements of the elastic *ed* cross section suggests that a contribution of 2γ exchange could appear for momentum transfer larger than 1 $(\mathrm{GeV/c})^2$. In order to measure this contribution, precise data on polarisation observables are crucial.

- Due to the specific properties of the quark structure of the Roper resonance (which has non zero longitudinal isoscalar form factor), the tensor analyzing power takes large negative values. A description which considers $t-$channel ω exchange and uses electromagnetic form factor for N^* based on a collective algebraic model nicely reproduces the experimental data.

"...it is important to separate symmetry from dynamics. A good fraction of hadronic properties depend on symmetry and not on dynamics. It is also important to order the various contributions according to their role..." [24].

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